MICROSTRUCTURE MODELING AND DESIGN OF TRIMODAL ALUMINUM METAL MATRIX COMPOSITES

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Introduction

Trimodal aluminum metal matrix composites (MMC) are emerging as a new class of lightweight structural materials with the potential for an excellent combination of high strength and ductility. Trimodal aluminum [1] is comprised of a fine scale MMC of nano-grained aluminum alloy reinforced with boron carbide (B_4C) particles. This composite is then dispersed in a matrix of coarse grained aluminum. This multi-scale hierarchal composite design, along with the selected processing route leads to a microstructure manipulation scheme that gives the materials designer a flexibility to tailor the material with a wide range of possible strength and ductility combinations. As an example, recent work has shown the specific processing route has a strong influence on the microstructure and mechanical properties of bulk trimodal MMC [2].

Due to the large number of material and processing parameters available, it is desirable to use modeling to predict and optimize macroscopic material response prior to manufacture. The present work discusses the implementation of microstructure based finite element simulations to numerically explore the mechanical response of trimodal MMC under quasi static and dynamic loading. Future work will explore the effect of material parameters such as ceramic particle size, particle morphology, and spatial phase distributions within the microstructure on the mechanical response and local deformation behavior of trimodal aluminum materials.

Modeling approach

In this work, SEM micrographs of trimodal material are discretized using object oriented finite element (OOF2) software and properties assigned to individual phases (Fig. 1). The current paper presents work using micrographs of the trimodal MMC developed by Ye et al. [1]. An area of 325 x 260 μm was simulated. The response of the same material was modeled previously by Joshi and Ramesh [3] using the secant Mori-Tanaka method, which is used for comparison to the current implementation.

Quasi-static compression simulations were run using ABAQUS/Standard, and dynamic compression simulations were conducted using ABAQUS/Explicit. Strain rate for dynamic simulations was $1000s^{-1}$. The B_4C particles are difficult to resolve and generally appear as clusters at the scale investigated currently. As such, to determine the effect of explicitly accounting for the ceramic particles, two material configurations (Fig. 2) were simulated: (1) a microstructure with all three phases accounted for (coarse grained (CG) Al, ultra-fine grained (UFG) Al, and B_4C), and (2) a two phase microstructure composed of CG aluminum and a composite phase (referred to as Level I composite). The properties of the Level I composite phase were obtained from Joshi's results [3] for the homogenization of B_4C in a UFG Al matrix. Aluminum and the Level I composite phases were modeled as elastic-plastic with isotropic hardening. Stress-strain curves for these materials are provided in Figure 2. B_4C particles were modeled as purely elastic, with Young's modulus of 480 GPa, Poisson's ratio of 0.17, and density of 2.5 g/cc. Properties of all materials were assumed to be rate independent.
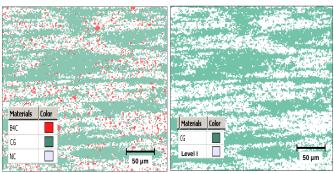

Fig. 1 Microstructures for three phase (left), and two phase simulations.

Results and Discussion

Stress strain curves (Fig. 2) for the three phase and two phase composites were obtained for quasi-static (Q/S) and dynamic compression in the direction of extrusion. It was observed that the yield strength of the three phase MMC is lower by ~7% than that of the hierarchal two phase composite. In the three phase composite, stress concentrations at the hard B_4C particles initiate yielding in the aluminum matrix at a lower macro stress level than in the two phase composite.

In this work, material properties of component phases are rate independent, thus any strain rate effects in the predicted response would be purely due to microstructural effects and interactions. For both the three phase and two phase composites, there is negligible difference between the compressive response in quasi-static and dynamic loading conditions (Fig. 2). This result is consistent with experimental observations [4] which showed little rate dependence over a large range of strain rates.

The results from Joshi [3] are also provided in Fig. 2 as a means to compare to the efficacy of the current numerical technique to that of a more traditional homogenization method (secant Mori-Tanaka). The results are in fairly good agreement and show that the current FEM approach is a viable means to accurately predict macroscopic MMC mechanical response. The minor discrepancies could be due to assumptions on microstructure in the M-T model as well as slight variations from material to material.

Figure 3 shows the local plastic strain at two time points during dynamic compression of the three phase material. Plastic strain initiates in the CG Al phase which eventually accumulates and regions of high plastic strain link to form bands. This behavior is qualitatively consistent with the experimental results presented by Zhang [4].

Conclusions

A microstructure based FEM model has been implemented for the direct prediction of mechanical response and deformation behavior of trimodal aluminum MMC and shown to agree with previously published model results as well as qualitative agreement with published experimental observations.
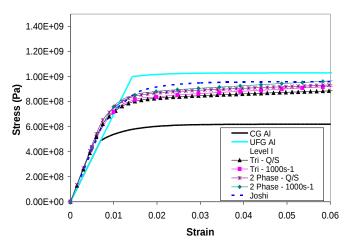

Fig. 2 Stress strain curves for input phase materials (solid lines), FEM predictions (symbols) for trimodal MMC, and Joshi's [3] M-T model results (dashed line).
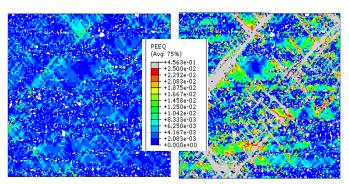

Fig. 3 Equivalent plastic strain contours in dynamic compression for three phase material at 1% (left), and 2% (right) macro strain.

References

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